Phytoremediation

Naval Facilities Engineering Service Center

Port Hueneme, CA

PPT/Leeson/91-1

Seminar Topics

- **Definitions**
- Applications – Potential and Real
- Remediation of Fuels and Chlorinated Solvents
- Hydrological Control
- Remediation of Metals
- Demonstration Projects
- Cost and Cost Comparisons
- Advantages and Limitations
- Planning and Implementation

Types of Phytoremediation

- **Phytotransformation** – uptake of contaminants from soil & groundwater by plants and their subsequent transformation in roots, stems, and leaves
- **Rhizosphere Bioremediation** – occurs in the root-zone; also known as phytostimulation or plant-assisted bioremediation; results in increase of soil organic carbon, and bacterial and fungal populations
- **Phytostabilization** – refers to holding of contaminated soils in place by vegetation, and immobilization (physically or chemically) of contaminants

Types of Phytoremediation (cont.)

- **Phytoextraction** – use of metal-accumulating plants that translocate metals from the soil to their roots and concentrate the metals to aboveground stems and leaves
- **Rhizofiltration** – use of plants to sorb, concentrate, and/or precipitate metal contaminants from surface waters (treatment wetlands) or groundwater

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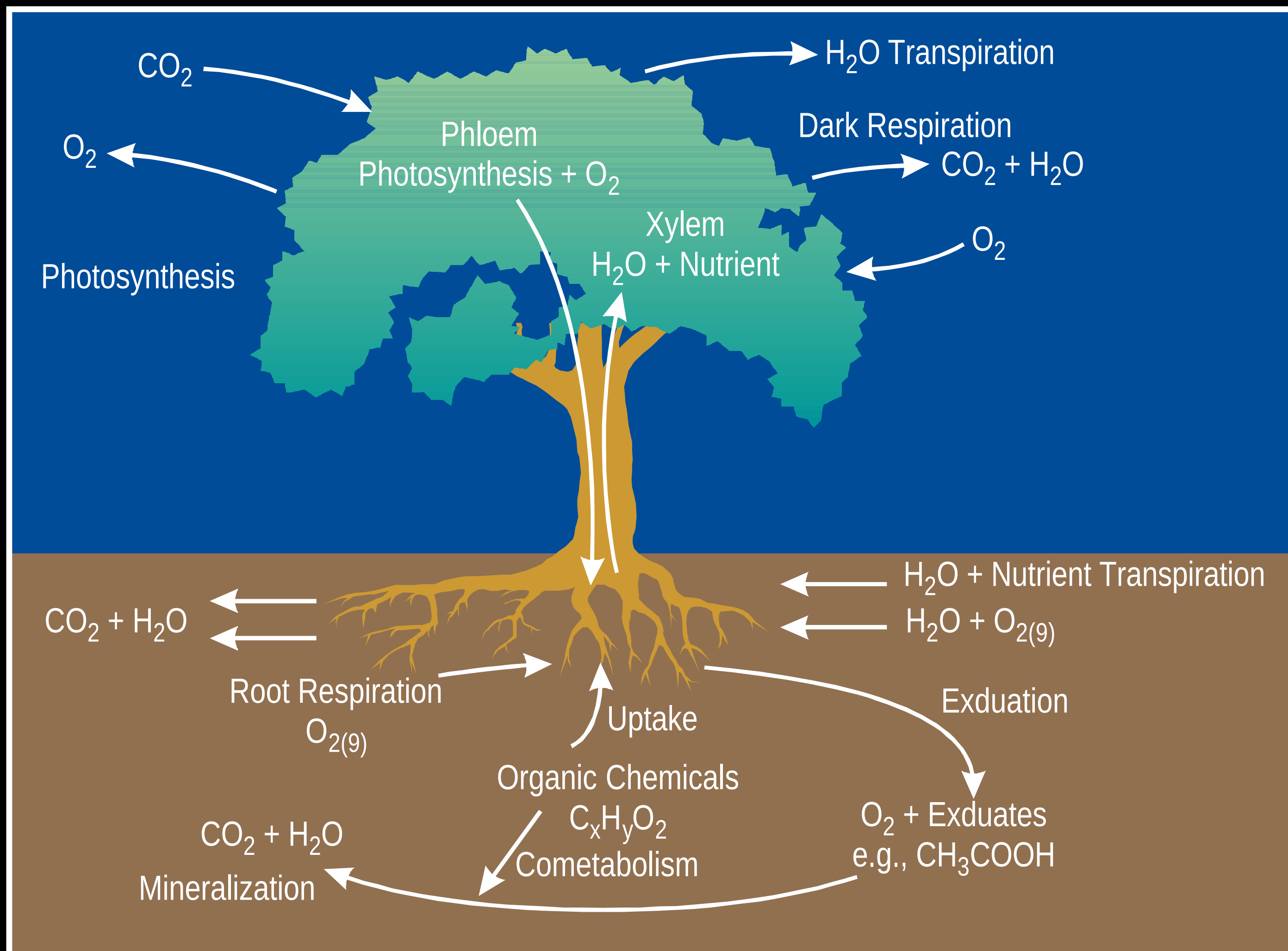
Why Phytoremediate?

Comparative Mass Disposal (10 Acres)

Excavation	Phytoextraction	
	Biomass	Ash
30,000 Tons	1,200 Tons	120 Tons

Overview of Phytoremediation-Related Plant Activities



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Potential Applications of Phytoremediation

Application	Contaminants	Typical Plants
Phytotransformation	• Herbicides (atrazine, alachlor) • Aromatics (BTEX) • Chlorinated aliphatics (TCE) • Nutrients (NO_3^-, NH_4^+, PO_4^{3-}) • Ammunition wastes (TNT, RDX)	• Phreatophyte trees (poplar, willow, cottonwood, aspen); • Grasses (rye, Bermuda, sorghum, fescue); • Legumes (clover, alfalfa, cowpeas)
Rhizosphere Bioremediation	• Organic contaminants (pesticides, aromatics, and polynuclear aromatic hydrocarbons [PAHs])	• Phenolics releasers (mulberry, apple, osage orange); • Grasses with fibrous roots (rye, fescue, Bermuda) for contaminants 0–3 ft deep; • Phreatophyte trees for 0–10 ft; • Aquatic plants for sediments

Potential Applications of Phytoremediation (cont.)

Application	Contaminants	Typical Plants
Phytostabilization	• Metals (Pb, Cd, Zn, As, Cu, Cr, Se, U) • Hydrophobic organics (PAHs, PCBs, dioxins, furans, pentachlorophenol, DDT, dieldrin)	• Phreatophyte trees to transpire large amounts of water for hydraulic control; • Grasses with fibrous roots to stabilize soil erosion; • Dense root systems are needed to sorb/bind contaminants
Phytoextraction	• Metals (Pb, Cd, Zn, Ni, Cu) with EDTA addition for Pb selenium (volatilization)	• Sunflowers • Indian mustard • Rape seed plants • Barley, hops • Crucifers • Serpentine plants • Nettles, dandelions

Potential Applications of Phytoremediation (cont.)

Application	Contaminants	Typical Plants
Rhizofiltration	• Metals (Pb, Cd, Zn, Ni, Cu) • Radionuclides (^{137}Cs, ^{90}Sr, U) • Hydrophobic organics	• Aquatic plants – Emergents (bullrush, cattail, coontail, pondweed, arrowroot, duckweed); – Submergents (algae, stonewort, parrot feather, Eurasian water milfoil, Hydrilla)

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Some Applications of Phytoremediation

Location & Application	Contaminants	Site Results
Amana, IA Nonpoint source control, 1-mi stream with poplars	NO_3^-, atrazine, alachlor, soil erosion	NO_3^- and 0.10-20% atrazine were removed
Amana, IA Municipal solid waste compost land application on poplars, corn, fescue	BEHP, B(a), PCB, chlordane	Small plot study, organics were immobilized
Beaverton, OR Municipal landfill cap with hybrid poplars	Organics, metals, BOD	Landfill cap successful, full scale
Slovenia Landfill cap, closure with hybrid poplars	Organics, metals, BOD	Two years of growth

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Some Applications of Phytoremediation (cont.)

Location & Application	Contaminants	Site Results
Iowa City, IA Landfill leachate, abatement with poplars	Chlorinated solvents, metals, BOD, NH_3	Poplars survived in lab, 1200 mg/L
Prince George's County, MD Sewage sludge in trenches, poplars on degraded lands	Nitrogen in sludge	170 tons/acre of sludge treated full scale 6 -year plantation
Corvallis, OR Organics in hydroponic system with poplars, Russian olive, soybean, green ash	Nitrobenzene and others	Essentially complete uptake in the lab

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Some Applications of Phytoremediation (cont.)

Location & Application	Contaminants	Site Results
New Mexico Contaminated soil with *Datura* sp. and *Lycopersicon* sp.	Trinitrotoluene (TNT)	Essentially complete treatment
Oak Ridge, TN Organics-contaminated soils with pine, goldenrod, Bahia grass	Trichloroethylene (TCE) and others	Enhanced biomineralization
Salt Lake City, UT Contaminated soil with crested wheatgrass	Pentachlorophenol and phenanthrene	Enhanced lab mineralization

Some Applications of Phytoremediation (cont.)

Location & Application	Contaminants	Site Results
New Jersey, IL Shallow groundwater and poplars	NO_3^-, NH_4^+	Decreased size of plume
McMinnville, OR Landfill leachate irrigation on 14 acres of poplars	NH_3 salts	Zero discharge, alternative to pumping to wastewater treatment plant
Childersburg, AL Soil with parrot feather	TNT	Enhanced degradation, pilot scale

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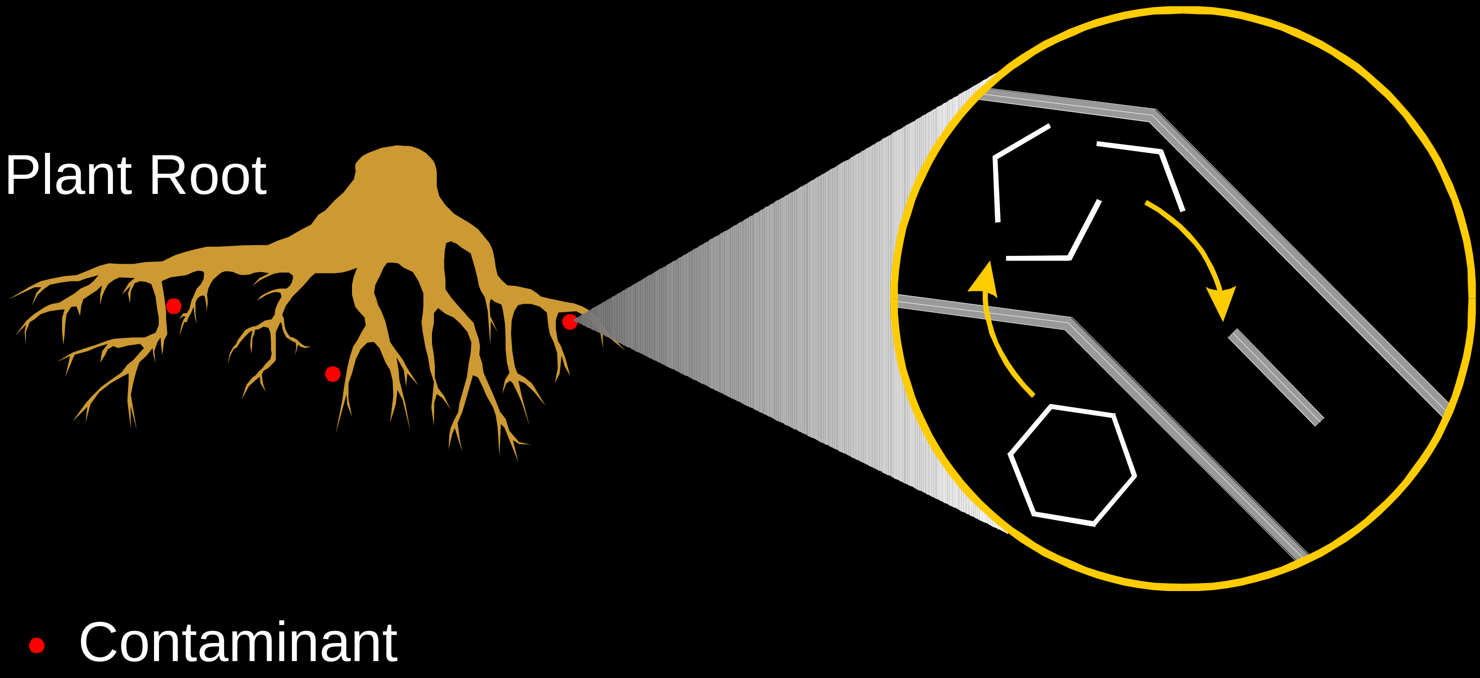
Phytoremediation of Fuel Hydrocarbon and Chlorinated Solvents



Enzymes in plant roots break down (degrade) organic contaminants. The fragments are incorporated into new plant material.

Plant-Specific Enzymes

Enzyme	Pollutant Degraded	Some Plants Known to Produce Enzyme
Dehalogenases	Chlorinated solvents	*Populus* sp. (hybrid poplars), *Myriophyllium spicatum* (parrot feather), Aleae *Nitella* (stonewort), Algae *Spirogyra*, *Anthrocerotea* sp.
Laccase	Oxidative step in munitions degradation	Algae *Nitella* (stonewort), *Myriohyllium spicatum* (parrot feather)
Nitroreductase	Munitions (TNT, RDX, etc.)	*Populus* sp. (hybrid poplars), *Myriohyllium spicatum* (parrot feather), *Lemna minor* (duckweed), Algae *Nitella* (stonewort), plus more
Nitrilase	Herbicides	
Peroxidases	Phenols	*Armoracia rusticana* (horseradish)

Phytoremediation of Diesel-Range Organics at Craney Island

Percent Fuel Remediated

Treatment	Nov. 95	Mar. 96	July 96	Nov. 96
Bermuda	0	4	6	31
Fescue	0	5	11	35
Clover	0	8	15	37
Unvegetated	0	2	9	25

NFESC Phytoremediation of Hydrocarbons

NFESC Phytoremediation of Hydrocarbons

Phytoremediation of Munitions Waterways Experiment Station

Compound	Initial Levels in Groundwater (mg L^{-1})	Remediation Rate (mg L^{-1})		
		Cattails/ Full Sunlight	No Plants/ Full Sunlight	No Plants/ No UV
TNT	2.7	0.27	0.26	0.17
2,4-DNT	16.7	1.28	0.58	0.17
2,6-DNT	5.2	0.53	0.48	0.17
2-NT	42.6			
4-NT	30.5			

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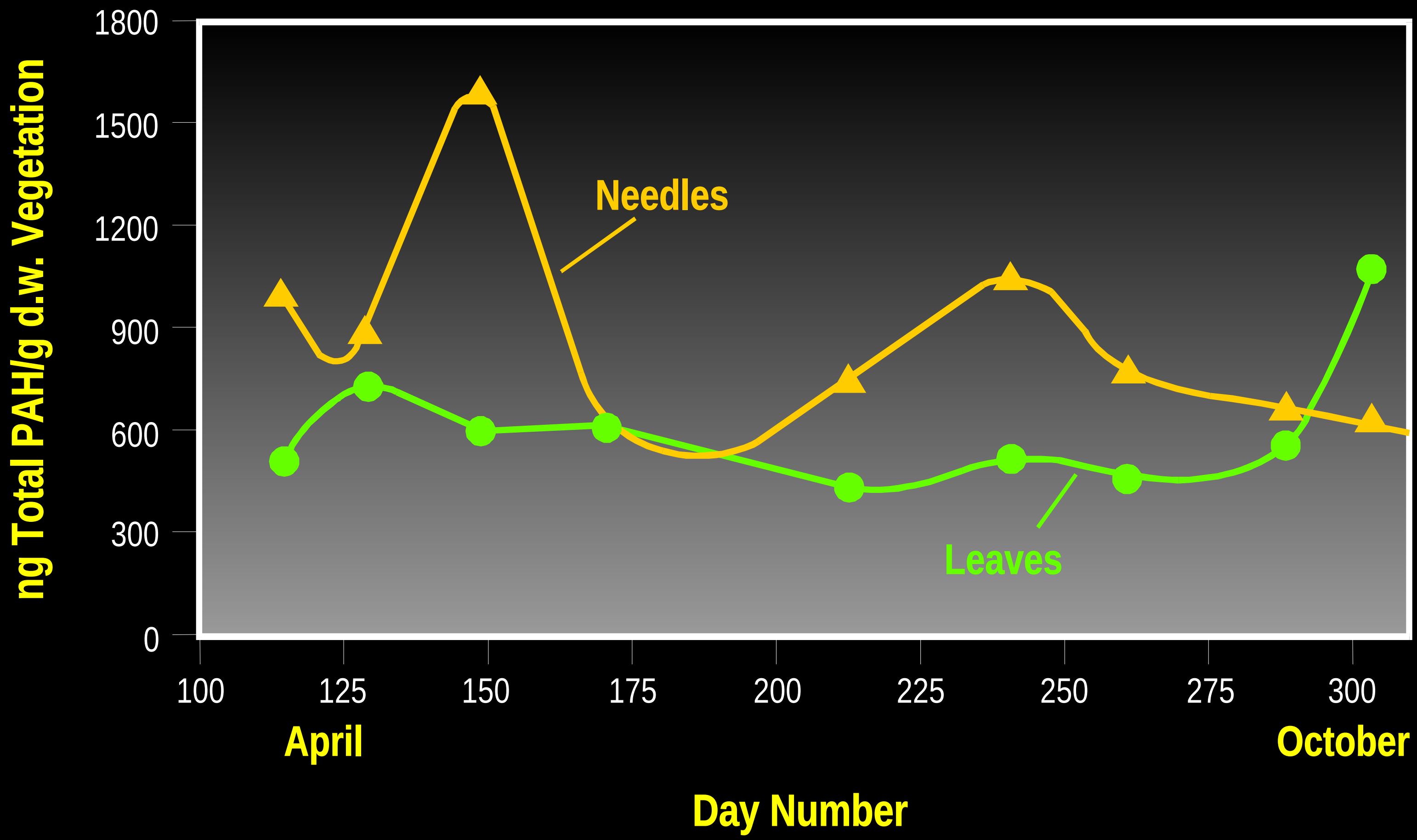
Seasonality of PAH Uptake



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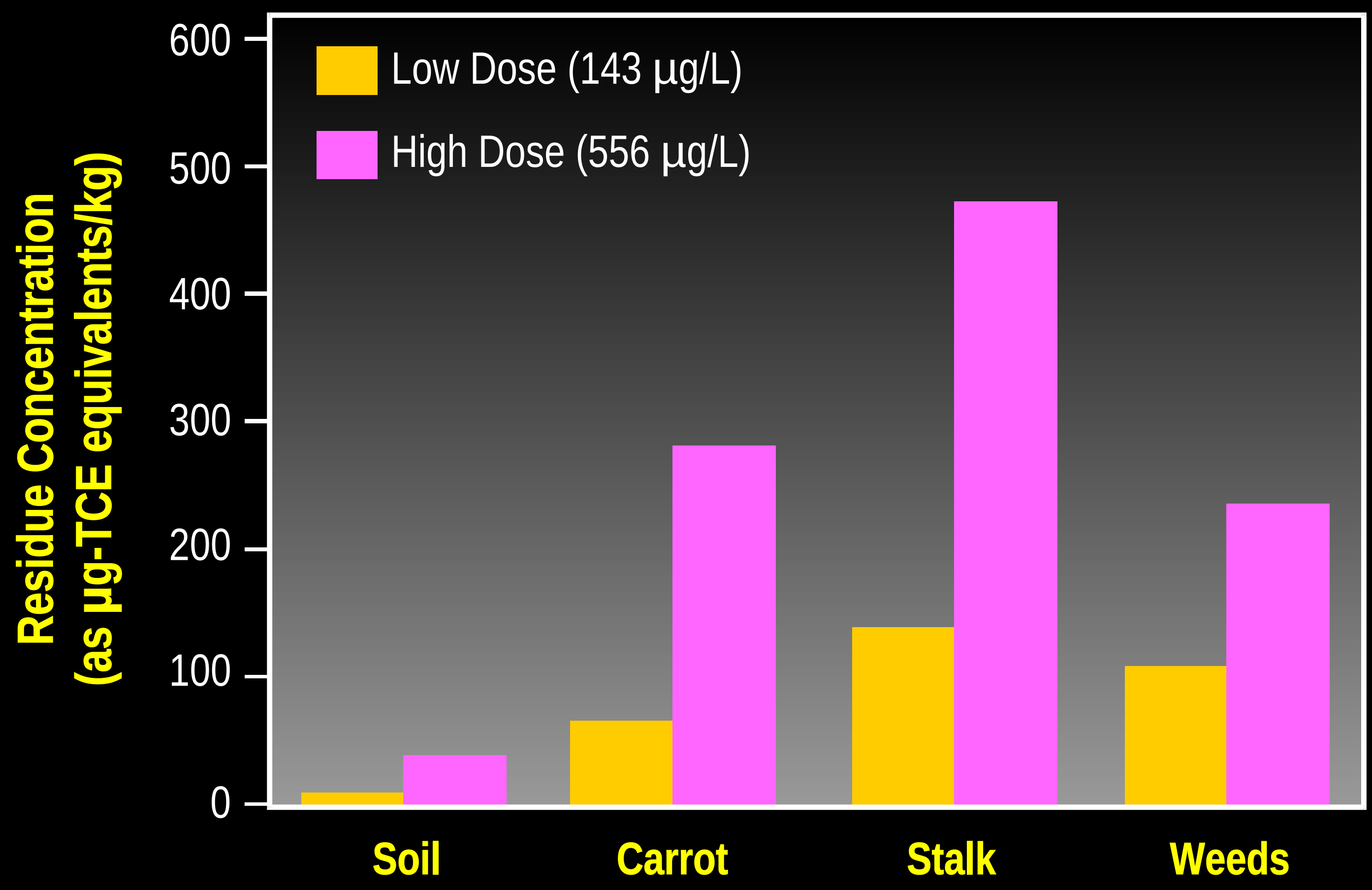
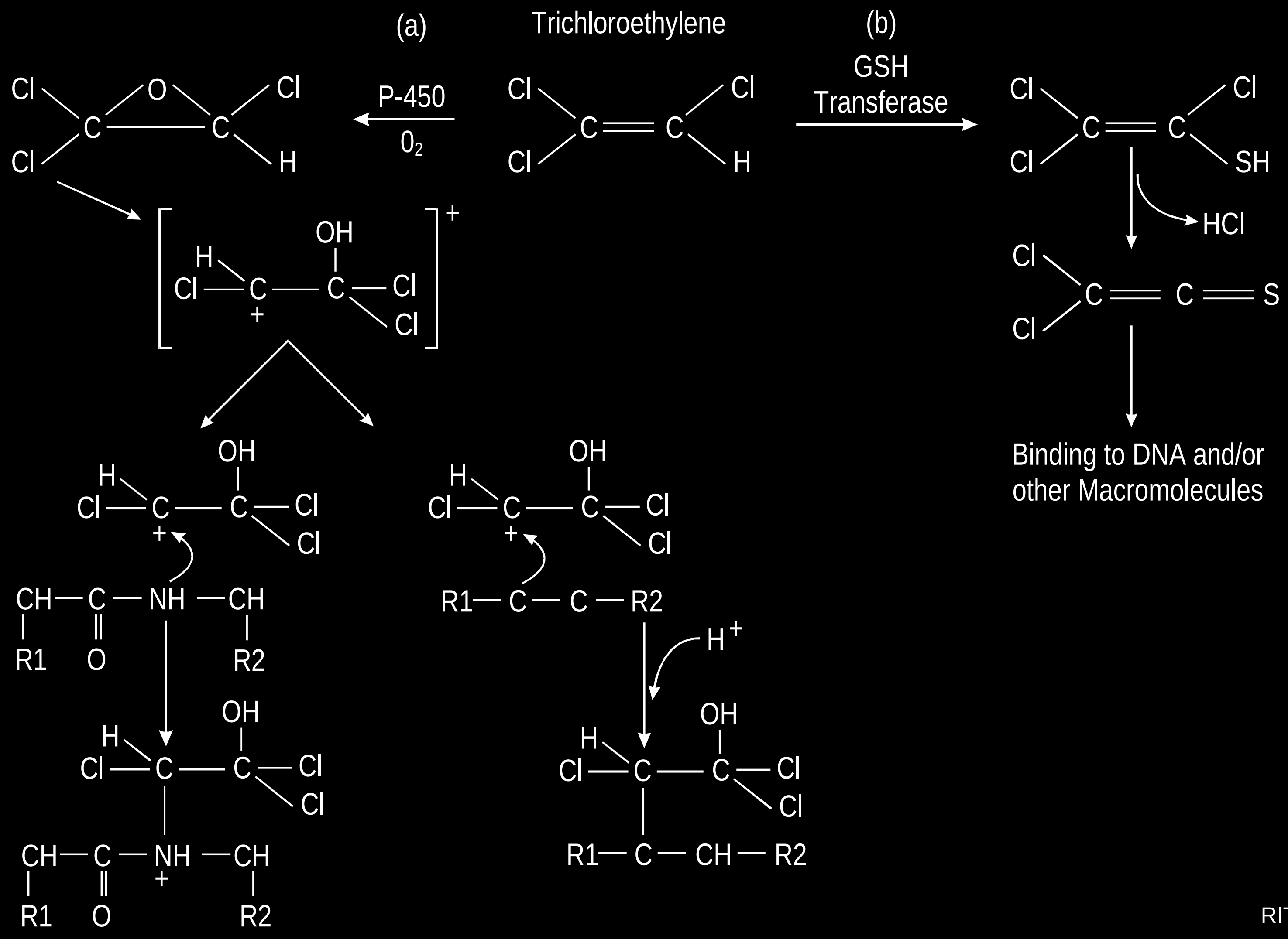
Phytoremediation of TCE



Plant-Catalyzed Degradation of TCE



Do Plants Enhance Beneficial Microbial Growth?

		Soil		Control
Organism	Plant	Bulk	Rhizosphere	No Plants
		log CFU/g soil		
Bacteria	Alfalfa	7.36	7.97	6.97
	Bluegrass	7.27	7.44	
Fungi	Alfalfa	4.47	5.10	4.62
	Bluegrass	4.39	4.48	

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Use of Plants for Hydrologic Control

Rate	Source
100 to 200 L/day/tree (~26 to 53 gallon/day) for 5-year-old trees	Newman et al. (1997)
1.6 to 10 gpd/tree (observed) sap flow rates for young hybrid poplars at the Aberdeen Proving Grounds in Maryland	Compton (1997)
10 to 11 kg/tree/day (observed) in early summer for 1-to-2 year old Eastern cottonwoods growing in Texas	Greg Harvey (personal communication)
40 gallons per day (observed) for 5-year-old trees in Utah in the summer	Ari Ferro – Workshop on Phytoremediation of Organic Contaminants (1996)

Large Leaves of the Hybrid Poplar

Advantages of Poplar Species

- More than 25 species worldwide
- Fast growing (3 to 5 meters/year)
- High transpiration rates (100 liters/day optimally for 5-year-old tree)
- Not part of food chain
- Trees can be used for paper production or as biomass for energy
- Long lived (25 to 30 years)
- Grow easily from cuttings
- Can be harvested and then regrown from the stump
- Easy to produce hybrids

Phytoremediation Using Poplars

Newly Planted Poplar

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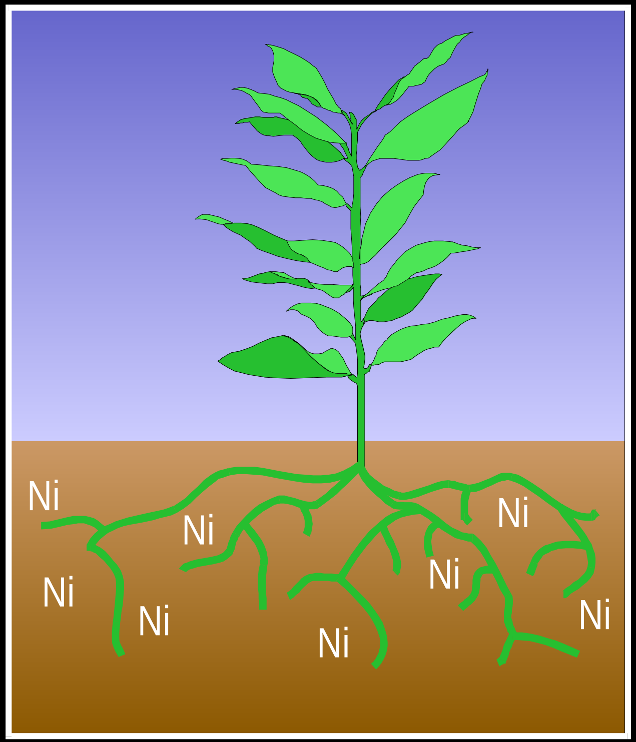
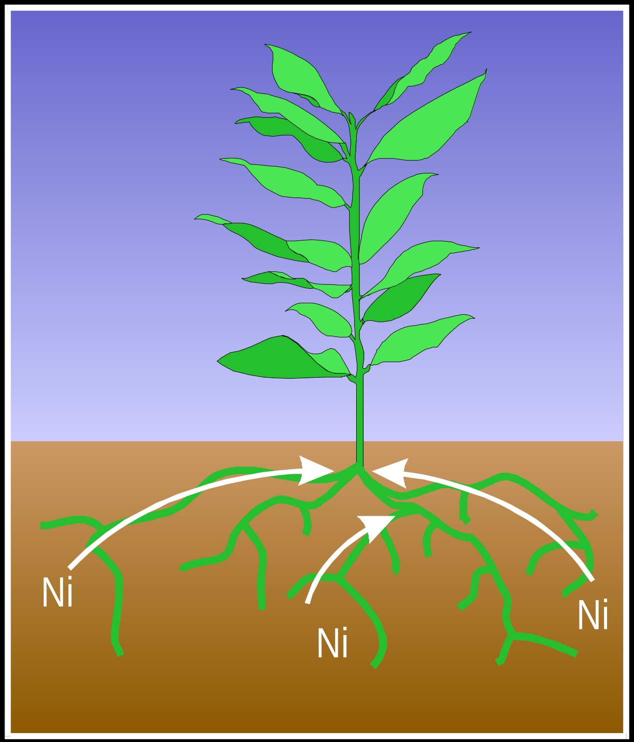
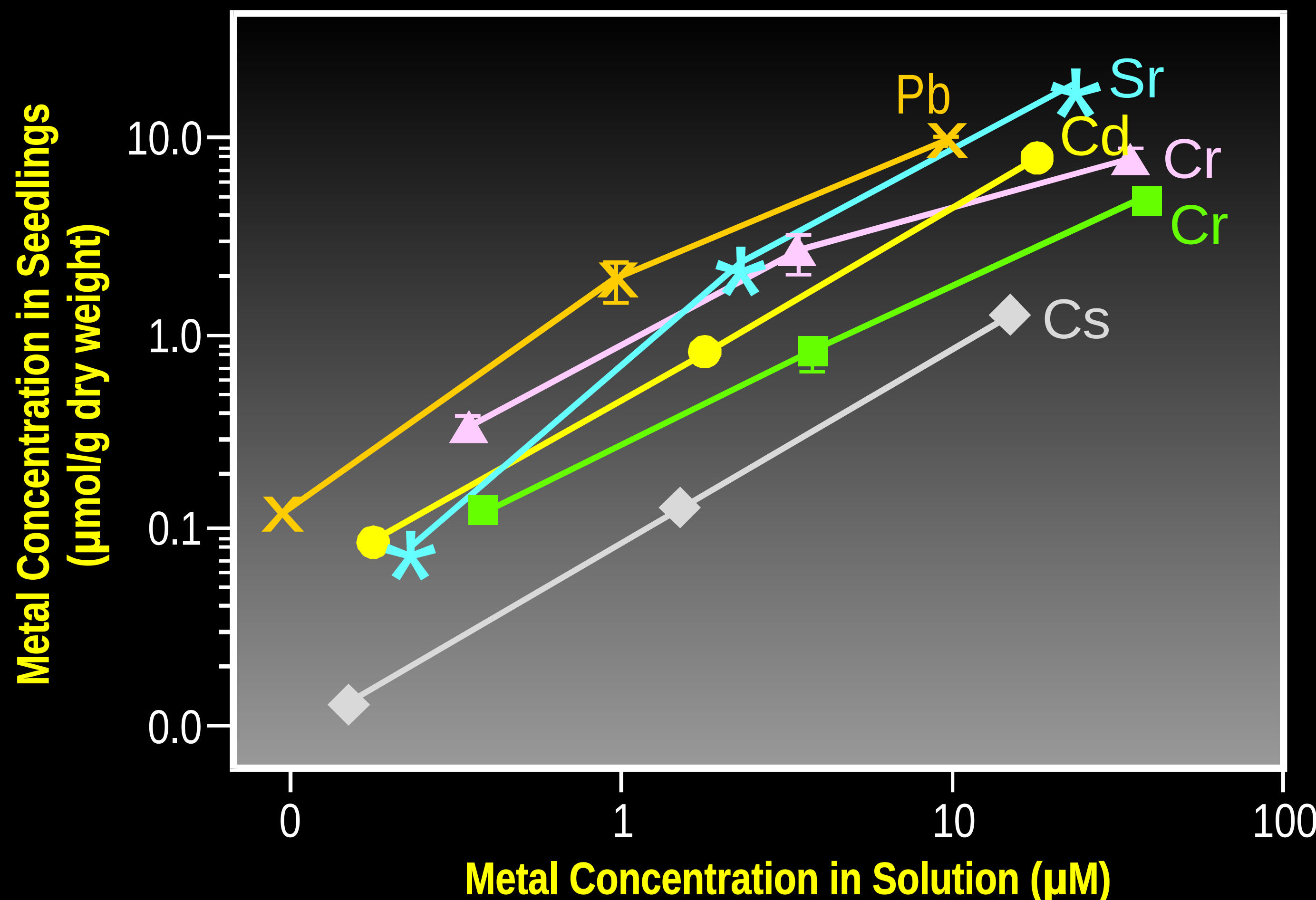
Phytoremediation of Metals





Nickel is removed from soil by moving up into plant roots, stems, and leaves. The plant is then harvested and disposed of and the site replanted until the nickel in the soil is lowered to acceptable levels.

Accumulation of Selected Metals Over 48 Hours by Indian Mustard *Brassica juncea*



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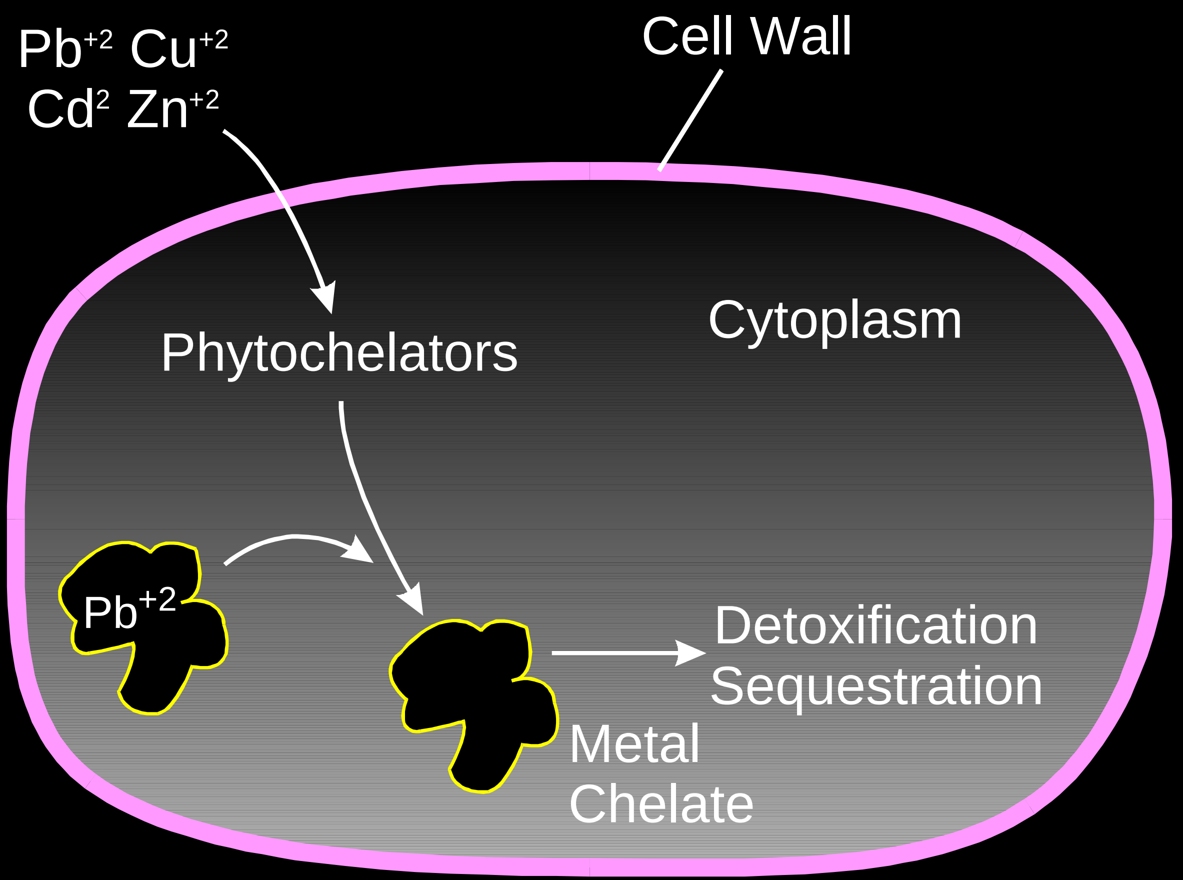
Phytoremediation of Heavy Metals

Individual Plant Cells



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Phytoremediation Applications and Demonstrations in the Field

Site & Application	Plants	Contaminants	Performance
Chernobyl, Ukraine Rhizofiltration demonstration pond near nuclear disaster	Sunflowers *Helianthus annuus*	^{137}Cs, ^{90}Sr	90% reduction in 2 weeks. Roots concentrated 8,000 fold
Ashtabula, OH Rhizofiltration demonstration DOE energy wastes	Sunflowers *Helianthus annuus*	U	95% removal in 24 hours from 350 ppb to <5 ppb
Trenton, NJ Phytoextraction demonstration 200 ft x 300 ft plot brownfield location	Indian mustard *Brassica juncea*	Pb	Pb cleaned up to below action level in one season SITE Program
Dearing, KS Phytostabilization demonstration 1-acre test plot abandoned smelter, barren land	Poplars *Populus* spp.	Pb, Zn, Cd Concs. >20,000 ppm for Pb and Zn	50% survival after 3 years. Site was successfully revegetated.

Phytoremediation Applications and Demonstrations in the Field (cont.)

Site & Application	Plants	Contaminants	Performance
Whitewood Cr., SD Phytostabilization demonstration 1-acre test plot mine wastes	Poplars *Populus* spp.	As, Cd	95% of trees died. Inclement weather, deer browse, toxicity caused die-off.
Pennsylvania Phytoextraction pilot mine wastes	*Thlaspi caerulescens*	Zn, Cd	Uptake is rapid but difficult to decontaminate soil
San Francisco, CA Phytovolatilization refinery wastes and agricultural soils	*Brassica* sp.	Se	Selenium is partly taken up and volatilized, but difficult to decontaminate soil
Aberdeen, MD – J-field site Phytotransformation groundwater capture on 1-acre plot	Hybrid poplars *Populus* spp.	TCE, PCA (1,1,2,2-Tetrachloroethane)	Only in second year. Demonstration project

Phytoremediation Applications and Demonstrations in the Field (cont.)

Site & Application	Plants	Contaminants	Performance
Carswell AFB – Ft. Worth, TX Phytotransformation groundwater capture on 4-acre plot	Hybrid poplars *Populus* spp.	TCE	Only in second year SITE Program
Milan, TN Phytotransformation engineered wetland at army ammunition plant	Elodeia, Bullrush, Canary Grass	TNT, RDX	>90% removal
Ogden, UT Phytotransformation (groundwater and soil) petrochemical wastes 4-acre site	Hybrid poplar	BTEX, TPH	Only in second year SITE Program
Portland, OR Phytotransformation on wastes of wood preservative	Hybrid poplar	PCP, PAH	Only in second year SITE Program

TCE Phytoremediation Sites

Site	Size of Planting on Site	Number of Trees Planted	Species or Hybrid
Aberdeen Proving Grounds – J Fields Site	~1 acre	183	*Populus trichocarpa x deltoides,* HP-510
Edward Sears Properties	~1/3 acre	118 deep rooted ~90 shallow rooted	*Populus charkowiiensis x incrassata,* NE 308
Carswell Air Force Base	~1 acre	660	*Populus deltoides*

TCE Phytoremediation Site Contacts

Aberdeen Proving Grounds – J Fields Site	Steve Hirsh, EPA Region 3 (215) 566-3352	Harry Compton, EPA ERT (908) 321-6751
Edward Sears Properties	George Prince, EPA ERT (908) 321-6649	Michael Moan Roy F. Weston/REAC (908) 321-4200
Carswell Air Force Base	Greg Harvey, Acquisition and Environmental Management Restoration Division (513) 255-7716 x302	Steven Rock U.S. EPA National Risk Management Laboratory (513) 569-7105

Phytoremediation – Results
Carswell AFB

Contaminant	Average Concentration (μg/L) December 1996	May 1997	July 1997
TCE	610	570	550
cis-DCE	130	140	170
trans-DCE	4	2	4

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Phytoremediation – Cost
Carswell AFB

Activity	Estimated Cost
Wholesale cost of trees (does not include delivery or installation)	$8/tree for five-gallon bucket tree $0.20/tree for whips
29 wells (including surveying, drilling, and testing)	$200,000
Subsurface fine biomass	$60,000

Cost Comparison

Cost Advantage of Phytoremediation (Rhizosphere Bioremediation) of Soils Using Fine-Rooted Grasses Compared to Other Techniques (E. Drake, Exxon, Anandale, NJ)

Type of Treatment	Range of Costs $/Ton
Phytoremediation	$10–35
In Situ Bioremediation	$50–150
Soil Venting	$20–220
Indirect Thermal	$120–300
Soil Washing	$80–200
Solidification/Stabilization	$240–340
Solvent Extraction	$360–440
Incineration	$200–1,500

Published Cost Estimates for Phytoremediation

Soils

- $1-10/m^3 ($2500-15,000/ha; S. Cunningham, DuPont)
- $15-20/ton (E. Drake, Exxon)
- $25-50/ton (Phytotech)
- $29-48/m^3 ($60,000-100,000/acre at depth of 50 cm; Salt et al.)
- $80/yd^3 (R. Levine, EPA)
- $100-150/m^3 ($200,000-300,000/acre; R. Cheney, USDA)

Water

- $0.64 per 1,000 gallons treated (V. Medina, EPA)
- $2.00-6.00 per 1,000 gallons treated (Phytotech)

Ecolotree's Cost Estimates of a Poplar Tree Phytoremediation System*

Activity	Cost
Installation of trees at 1,450 trees/acre	$12,000 to $15,000
Predesign	$15,000
Design	$25,000
Site visit	$5,000
Soil cover and amendments	$5,000
Transportation to site	$2.14/mile
Operation and maintenance	$1,500/acre with irrigation $1,000/acre without irrigation
Pruning (not every year)	$500
Harvest (during harvest years)	$2,500

* Estimates will vary with type of contaminant, goal of project (i.e., containment vs. removal), and location.

Applied Natural Science's Cost Estimates of a Poplar Tree Phytoremediation System*

Activity	Cost
Tree remediation program design and implementation	$50,000
Monitoring equipment	Hardware – $10,000 Installation – $10,000 Replacement – $5,000
Five-year monitoring	Travel and meetings – $50,000 Data collection – $50,000 Annual reports – $25,000 Sample collection and analysis – $50,000

* Estimates will vary with type of contaminant, goal of project (i.e., containment vs. removal), and location.

Five-Year Cost Comparison of Phytoremediation

Hybrid Poplar Trees vs. Conventional Pump and Treat

1. Phytotransformation

Design and Implementation	$ 50,000
Monitoring Equipment	
Capital	10,000
Installation	10,000
Replacement	5,000
5-Year Monitoring	
Travel and administration	50,000
Data collection	50,000
Reports (annual)	25,000
Sample analysis	50,000
TOTAL	$250,000

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Five-Year Cost Comparison of Phytoremediation (cont.)

Hybrid Poplar Trees vs. Conventional Pump and Treat

2. Pump and Treat (3 wells and Reverse Osmosis System)

Equipment	$ 100,000
Consulting	25,000
Installation/Construction	100,000
5-Year Costs	
Maintenance	105,000
Operation (electricity)	50,000
Waste disposal	180,000
Waste disposal liability	100,000
TOTAL	$660,000

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Estimated Costs of Treating PCE in the Groundwater

Treatment Technology	Total Present Cost (x $1,000)	Cost/Pound PCE Removed	Cost/1,000 Gallons Treated
Pump and treat with air stripping and carbon absorption	$9,800	$1,600	$8.90
Iron reactive barrier	$3,900	$640	$5.30
Biobarrier (substrate-enhanced anaerobic bioremediation)	$3,100	$520	$4.20
In situ bioremediation (substrate-enhanced, recirculating source zone)	$1,300	$220	$1.80
Natural attenuation (intrinsic bioremediation)	$890	$150	$1.20

(Assumes PCE plume averages 1 ppm, the remedial goal is 5 ppb, there is no pooled PCE in the aquitard, plume is in the aqueous phase, and the remediation time is 30 years.)

Cost Advantage of Phytoextraction for Metals
(Phytotech Technical Summary, 1997)

Type of Treatment	Cost/m^3 ($)	Time Required (months)	Additional Factors/Expense	Safety Issues
Fixation	90-200	6-9	Transport/excavation Long-term monitoring	Leaching
Landfilling	100-400	6-9	Long-term monitoring	Leaching
Soil extraction, leaching	250-500	8-12	5,000 m^3 minimum Chemical recycle	Residue disposal
Phytoextraction	15-40	18-60	Time/land commitment	Residue disposal

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Advantages and Limitations of Phytoremediation

Advantages	Limitations
In situ	Limited to shallow soils, streams, and groundwater
Passive	High concentrations of hazardous materials can be toxic to plants
Solar driven	Mass transfer limitations associated with other biotreatments
Transfer is faster than natural attenuation	Effective only for moderately hydrophobic contaminants
High public acceptance	Toxicity and bioavailability of degradation products is not known
Fewer air and water emissions	Contaminants may be mobilized into the groundwater
	Potential for contaminants to enter food chain through animal consumption
Soils remain in place and are usable following treatment	Unfamiliar to many regulators
Compatible with RBCA	Hyperaccumulators are often slow growers
Compatible with engineered technologies	

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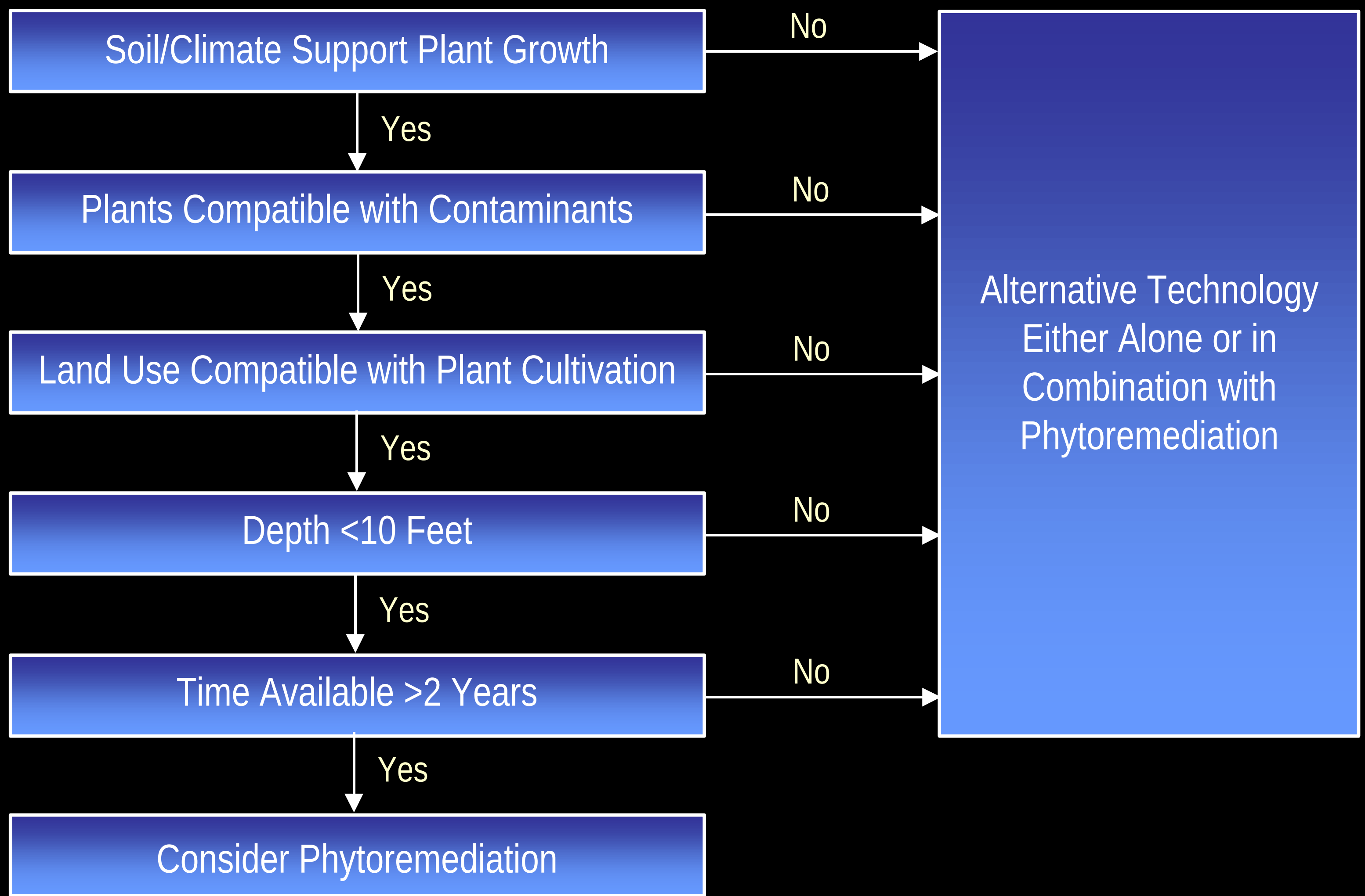
Considering Phytoremediation for Your Site



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Additional Considerations

- Need to dispose plant biomass
- Available space for aqueous treatments: is hydraulic rate of removal sufficient?
- Crop damage due to animals
- Toxicity of contaminant in plant biomass: toxicity to animals, human food chain
- Need for pest control, controlled access.

Phytoremediation Project Planning

- Preliminary site investigation
- Coordination with interested parties
  - Design, engineering, management
- Laboratory treatability
  - Evaluate plant growth and performance
  - Soil and/or water properties
- Hydrogeological modeling and irrigation requirements
- Implementation
  - Planting, cultivation, sampling, harvesting
- Monitoring and analysis
- Biomass disposal
  - Drying, composting, transport, incineration, landfill, smelter.

Monitoring

Parameter	Analysis
Plant growth	Diameter, height, weight, root mass
Plant tissue	Degradation products, sequestered contaminants
Plant sap flow measurements	Correlate sap flow to meteorological data
Transpirational gas	Contaminant volatilization
Groundwater and soil	Wells, lysimeters, soil samples to determine biodegradation activity, residual contaminants

Future/Ongoing Improvements to Phytoremediation to Enhance Acceptance

- Use of chelators to enhance metal solubility
- Combination with other in situ technologies (e.g., microbial bioremediation, electrokinetics)
- Selection of improved plant varieties
- Genetic engineering of improved varieties
- Validate rhizosphere effects
- Determine acceptable end points
- Identify critical parameters, species, climate, soils.

Phytoremediation Using Cash Crops

Phytoremediation Resources on the Web

Page Name	Address
Bioresource Engineering – Oregon State University	www.bre.orst.edu
Dr. Ilya Raskin's Laboratory	cook-college.rutgers.edu/~halpern/index.html
Envirobiz – Chevron Grows New Remediation Technology: Alfalfa and Poplars	www.envirobiz.com/newsdaily/960502el.htm
Environmental Security Technology Certification Program – Cleanup Projects page	scaffold.walcoff.com/estep2/projects/cleanup/index.html
Ground-Water Remediation Technologies Analysis Center: Phytoremediation – Technology Overview	www.gwrtac.org/html/tech_over.html#PHYTOREM
HSRC's Phytoremediation page	www.engg.ksu.edu/HSRC/phytorem

Phytoremediation Resources on the Web (cont.)

Page Name	Address
Hyperaccumulators and Phytoremediation	bob.soils.wisc.edu/~barak/soilscience326/agres.htm
Phytoremediation at Utah State University	www.usu.edu/~cpl/phytorem.html
Phytotech, Inc.	www.phytotech.com
Poplars and Willows on the World Wide Web	poplar2.cfr.washington.edu/
The RTDF Phytoremediation of Organics Action Team	www.rtdf.org/phyto.htm
USDA Economic Research Service – Industrial Uses of Agricultural Materials page	www.econ.ag.gov/epubs/pdf/IUS6/INDEX.HTM

Points of Contact

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